Redatumming through a Salt Canopy – Another Salt Flank Imaging Strategy

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ABSTRACT

We describe a new short cut strategy to image the sediments and salt edge around a salt flank through an overburden salt canopy. We demonstrate its performance and capabilities on a synthetic acoustic seismic data from a Gulf of Mexico (GOM) style model. In this strategy, we first redatum the surface shots from a walk away Vertical Seismic Profile (WVSP) survey to be as if the source and receiver pairs had been located in the borehole at the positions of the receivers. This process creates effective downhole shot gathers by completely moving the surface shots through the salt canopy without any knowledge of the overburden velocity structure. After redatumming, we apply reverse time prestack depth migration to the effective downhole shot records using a simple linear $v(z)$ gradient velocity model. This first pass of migration reveals the salt dome edge quite well. Once the salt dome edge is defined, a second pass of reverse time prestack depth migration is performed with an updated velocity model that now consists of the $v(z)$ gradient and the salt dome. The second pass migration brings out the dipping sediments abutting the salt flank because these reflectors were illuminated by energy that bounced off the salt flank forming prismatic reflections. In this target-oriented strategy, the computationally fast redatumming process eliminates the need for the traditional complex process of velocity estimation, model building, and iterative depth migration to remove the effects of the salt canopy and surrounding overburden.

1. INTRODUCTION

An accurate image of reservoir sediment structures at the flank of a salt dome is very important for computing reserves estimates and production development planning. Imaging subsalt sediments in the deep water GOM requires seismic methods which handle distortions caused by complex salt tectonics. There are many variations of prestack depth migration methods to handle seismic data, including Kirchhoff (Gray et al., 1994; Bevc, 1997), Gaussian beams (Hill, 1990, 2001; Sun et al., 2000; Gray, 2005), and reverse time (Baysal et al., 1983; Hokstad et. al., 1998; Biondi and Shan, 2002). Also key to imaging subsalt GOM sediments is the proper handling of turning ray energy (Hale et. al., 1992; Xu and Jin, 2006) and velocity model building (Siddiqui et. al., 2003; Wang et al, 2006). Typical imaging projects require multiple passes of migration, velocity analysis and model building in order to handle complex salt overburden. One problem facing deep GOM imaging objectives is that with surface seismic data there is only limited velocity resolution remaining at the depths of many subsalt plays (Wang et al., 2006). Also the complex overburden, e.g. a salt canopy, decreases illumination quality and makes velocity model building difficult (Guitton et. al. 2006a). WVSP data has the ability to increase the frequency bandwidth (i.e. resolution) and decrease uncertainty by removing half of the seismic ray path which otherwise would have to travel back to the surface receivers. However, prestack depth migration of WVSP data suffers the same need for iterative velocity model building as surface seismic data.

Redatumming of a WVSP dataset is a new strategy (Willis et al., 2005, 2006; Lu et al., 2006; Hornby, 2006) which can eliminate the need for deriving an overburden velocity model. It is a generalization of several related technologies: acoustic daylight imaging (Claerbout, 1976, Rickett, 1996), time reversed acoustics (Fink, 1999, 2006), seismic interferometry (Schuster et al., 2003, 2004; Derode et al., 2003; Sneider, 2004; Wapenaar et al., 2004, 2005), and Virtual Sources (Bakulin et al., 2004; Calvert et al., 2004). All of these techniques employ the time symmetry of the wave equation together with source-receiver reciprocity to estimate the impulse response between two passive receivers. This principle allows the effective acquisition geometry to be drastically changed in traditionally recorded data sets. Bakulin and Calvert (2004, 2005) showed examples for redatumming surface sources to receivers in a near-horizontal well just beneath the overburden. This may be an excellent way to remove the overburden artifacts on time lapse seismic imaging studies to detect the changes in reservoir properties.

In this paper, we propose a new strategy to image a salt flank and its associated abutting sediments. It contains two parts – redatumming and migration. In a typical redatumming workflow, first a WVSP dataset is collected with sufficient aperture to capture turning ray energy from the salt flank reflections. The data is then sorted into common receiver gathers. A succession of pair wise traces from the same surface shots are cross-correlated. The resulting correlograms are then stacked to obtain the effective trace representing a downhole shot recorded at a downhole receiver. This process is repeated for all combinations of downhole receivers to create effective shot gathers for all borehole receiver locations. In the second part, two passes of migration are performed – the first pass delineates the salt edge using simple $v(z)$ velocity model, and the second pass reveals the sediments using velocity model that includes the salt edge picked from the first migration.

2. METHODOLOGY

We will illustrate our processing strategy using a synthetic, acoustic example. We create a 2-D data set representing a multi-level walk-away VSP for a model as shown in Figure 1. The model is composed of a simplified GOM vertical velocity gradient, an embedded overhanging salt dome (SD-I) together with a salt canopy nearby (SD-II). The velocity gradient and values are taken from the EAGE/SEG salt dome model which represents typical GOM velocities. Both salt domes have a P-wave velocity of 4480 m/s. The background velocity is described by $v(z) = v_0 + Kz$, where v_0 is the velocity of the top layer (v_0 = 2200 m/s) and K is the velocity gradient (K = 0.4). Six reflectors are introduced on top of the $v(z)$ gradient as 15%-higher velocity spikes and the reflectors dip up towards the salt dome flank. Taking the well head as the origin, the walk away line consisting of 399 shots extends at the surface from -7.5 km to +2.5 km and the shot interval is 25 m. The receivers are placed in the borehole from a depth of 0.5 km to 4.5 km at a 25 m interval (total 161 receivers).

To image the salt dome edge (SD-I) and the corresponding abutting sediments, our proposed strategy consists of the following parts:

1. Redatum the surface sources into the borehole
   (a) Perform appropriate cross correlations on common receiver gathers and stack the corresponding correlograms.
   (b) Mute direct arrivals and non-causal artifacts from redatummed effective downhole shot gathers in preparation for migration.
2. Migrate the redatummed effective downhole shot gathers
   (a) Perform reverse time depth migration of the effective downhole shot gathers to obtain image of the salt dome edge using simple linear $v(z)$ gradient velocity model;
   (b) Pick salt dome edge horizon from migrated image and build new model containing the linear $v(z)$ background velocity and the salt dome (SD-I);
   (c) Perform second pass of reverse time depth migration, using a two-way wave equation algorithm, to obtain image of salt dome edge and dipping sediments.

The first part applies redatumming to the WVSP traces. This will create new effective shot gathers which are as if both the sources and receivers were located in the borehole. We sort the WVSP data into common downhole receiver gathers. Next we select one of the actual downhole receiver locations to be an effective source location. Then we select another actual downhole receiver location to be an effective receiver location. Two representative common downhole receiver gathers at depths of 2 km and 3 km, are shown in

Figure 2. At the lowest level, operations on these two common receiver gathers illustrate the basic building blocks of the redatumming process.

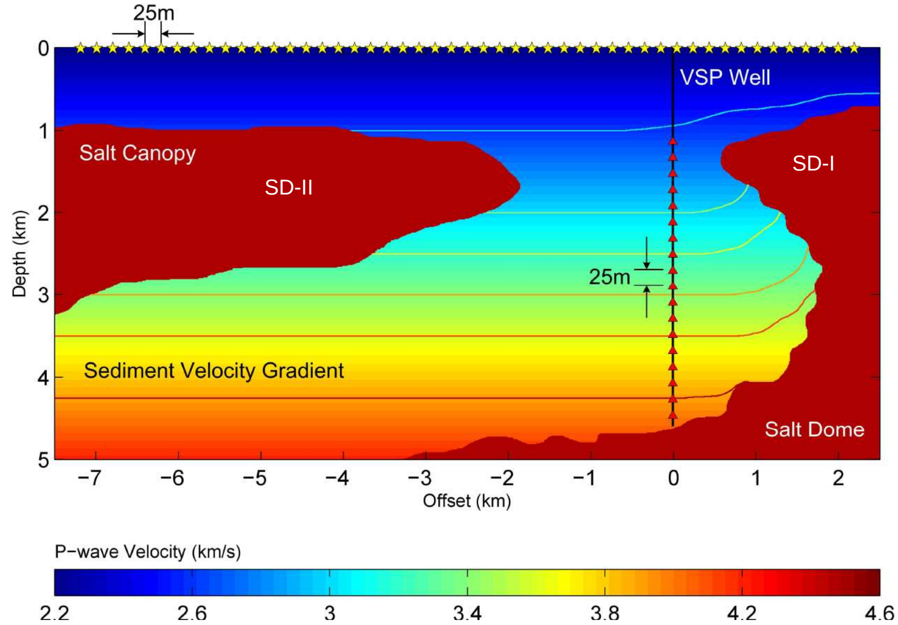

Figure 1: Walk-away VSP acquisition geometry for a synthetic GOM model that composed of a simplified vertical velocity gradient and an embedded overhanging salt dome (SD-I) together with a second salt canopy nearby (SD-II).

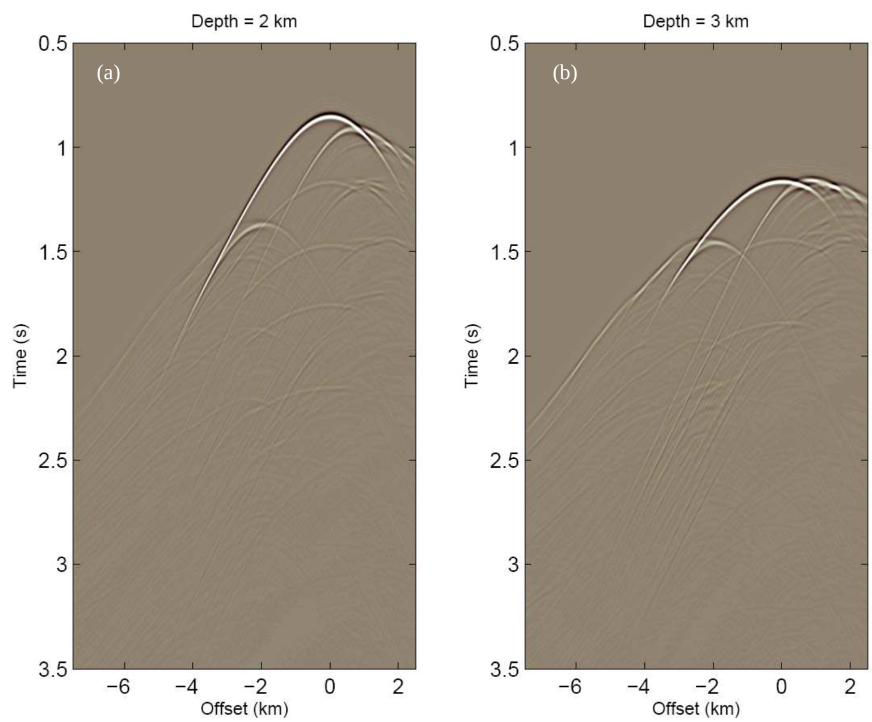

Figure 2: Common downhole receiver gathers at depths of (a) 2 km and (b) 3 km. Horizontal axes denote the offset of the corresponding shot for each trace.

Suppose we want to estimate a recording of an effective shot located at a depth of 2 km by an effective receiver at a depth of 3 km. We use these two common receiver gathers from the original WVSP corresponding to the desired effective receiver location (Figure 2a) and the effective shot location (Figure 2b). There are a pair of traces, one trace from each of these two common receiver gathers, corresponding to each surface shot. Each of these pairs of traces is cross-correlated. The horizontal axes in the both common receiver gathers shown in Figure 2 denote the shot offset for each trace. We start with the left-most shot offset at -7.5 km. We extract the corresponding traces from the common receiver gathers at depths of 2 km (left panel) and 3 km (right panel). Cross-correlating these two traces gives one correlated trace, or correlogram, which is shown as the left-most trace in Figure 3a. We repeat this operation for all shot offsets in this set of common receiver gathers which fills in the rest traces in Figure 3a. All of these correlograms are stacked together which produces a single trace shown in Figure 3b. This single stacked trace becomes our estimate of the recorded trace due to an effective shot located at 2 km depth and a receiver at 3 km depth. This trace is shown at a depth of 3 km in the upper panel of Figure 4 which represents the complete redatummed shot record.

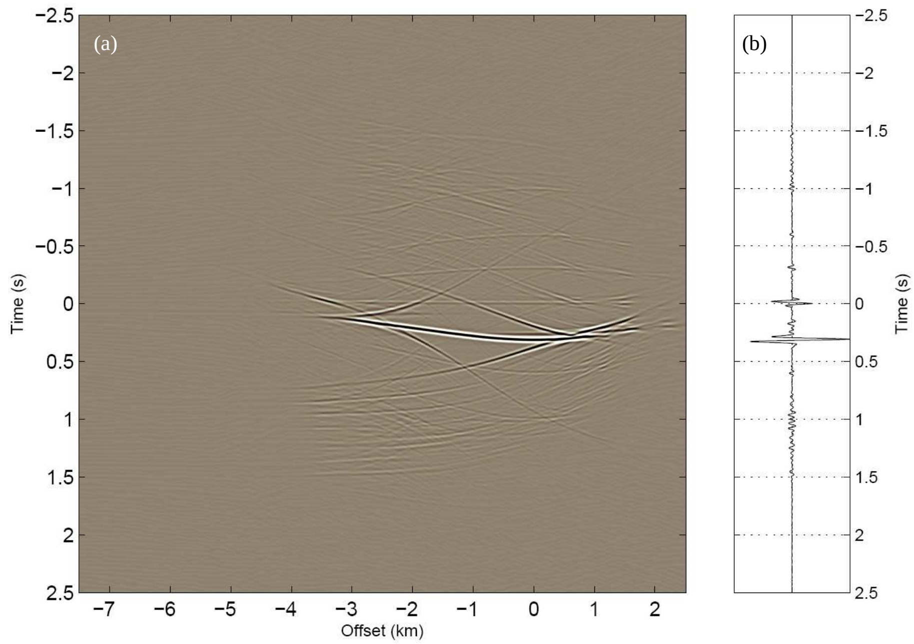

Figure 3: (a) Correlograms created by cross-correlating corresponding traces from Figure 2a and 2b; (b) estimate of the recorded trace due to an effective shot located at 2 km depth and a receiver at 3 km depth by stacking all the traces in Figure 3a.

To estimate the traces for the next downhole receiver offset, we keep the common receiver gather corresponding to the effective source location (at 2 km) and grab the common receiver gather for the new desired effective receiver location. We then repeat the set of corresponding correlations as described above. By doing this for all receiver depth levels, we create an effective common downhole shot gather, such as in the upper panel of Figure 4. This mimics a shot gather collected by the downhole receiver array due to a downhole source firing at the location that we choose to be the effective source location (at 2 km). For comparison, we show in the lower panel of Figure 4 the actual common shot gather modeled with a true source at a depth of 2 km, which we define as the benchmark case.

Comparing Figure 4a and 4b, we observe that these common shot gathers are similar, except that our redatummed downhole shot gathers include many spurious events not present in the actual downhole record. Part of these spurious events come from the acquisition aperture which is limited to only surface shots. Although contaminated by these spurious events, the main reflections off the target salt flank (events which arrive after 0.75 sec) are present. We also observe that in Figure 4b, the three linear downgoing events coming off of the first arrival are absent in the redatummed traces. These events are the downgoing specular reflections off of the underside of the flat laying sediments crossing the borehole location. The omission of this energy is due to the fact that not very much of this energy is excited by a surface source. An actual downhole source creates upgoing energy which is reflected back downward. Just as in the theory for migration, to be more correct we should put sources (or receivers) completely surrounding the area we wish to image. If this were possible, we would be able to reconstruct these down going reflections. (Van Manen et al. (2004) used this concept of sources all around the model for efficient simulation of wave propagation.) However, since this is not practical for field scale surveys we must evaluate the effect of this limited aperture on the final results.

To obtain a complete redatummed downhole survey, we repeat this for all possible effective downhole source locations. Note that in order to redatum the shot to be in the borehole we do not have to apply velocity analysis or complicated processing (such as statics or NMO corrections). In fact, there are no model dependent processing parameters required to move the surface shots into the borehole. We do not even need to know that there is a salt canopy complicating the ray paths of the energy. For the acoustic case, this feature allows the redatumming methodology be performed in a fully automated fashion that requires virtually no human effort.

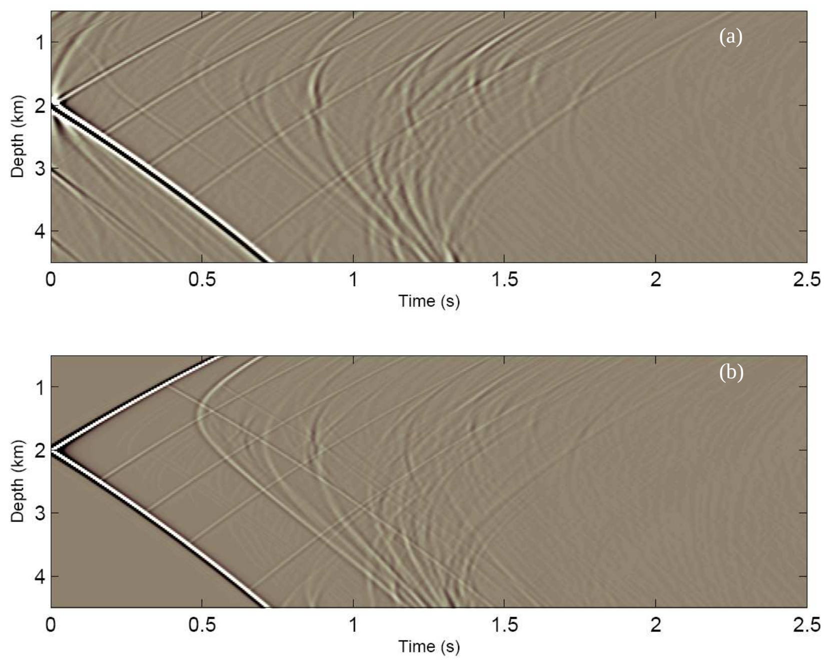

Figure 4: Common downhole shot gathers obtained (a) by redatumming WVSP data to be as if there is an effective source at a depth of 2 km, and (b) by placing an actual source at a depth of 2 km (benchmark case).

The final step of the redatumming process is to prepare the data for migration. The redatummed shot gathers contain artifacts, described above, which would contaminate the migration. Many of these artifacts arrive before the direct arrivals. It is easy to eliminate these by simply applying a mute which removes everything up to and including the direct arrivals on the redatummed downhole shot gathers. We have not explored other methods of removing artifacts which occur later in time on the records yet.

This redatumming methodology gives kinematically correct results (Wapenaar et al., 2005), which is acceptable for structural imaging applications. In this paper we investigate the acoustic case – for elastic energy additional steps are needed to handle the multi-components. For stratigraphic and time-lapse applications more work is needed to ensure correct relative amplitudes.

The success of the redatumming step is determined by how much energy is reflected off the reflectors near the salt flank and captured by the receivers in the borehole. Because we are trying to image underneath the salt overhang, this is generally only possible in a medium with a linear $v(z)$ vertical velocity gradient. In other geometries and velocity regimes, other solutions are possible. For example, Bakulin and Calvert (2005) successfully capture the reflection energy and imaged horizontal reflectors using a horizontal well.

The second part of our strategy is to perform two passes of depth migration. The first pass defines the salt edge geometry and the second pass refines the image to capture the sediments. We have experimented with both Kirchhoff and reverse time depth migration algorithms. For the first pass it is possible to use the either method. However, we have found that the sediment images are only obtainable using a reverse time algorithm which employs the two way wave equation. This is because the sediments are only illuminated by prismatic reflections (Cavalca and Lailly, 2005) which are created by energy which has bounced off the salt and then reflected by the sediments and visa versa. In prestack reverse time migration both the shot and recorded wave fields are extrapolated and zero lag correlations between the wavefields form the image. To save CPU time and disk space, we used an analytically derived travel time table for the forward propagated shot wave field simulation. We used the full wave equation to back propagate the redatummed field data. Using a travel time table is reasonable since our velocity model for the forward shot is a simple, linear $v(z)$ gradient function. However, we will image only half of the prismatic reflections – those that bounce off the salt first and will not capture those that bounce off the sediment first.

For the first pass of migration, we need a generalized migration velocity model. To image and define the salt edge from the redatummed shot position, only the target oriented, background velocity between the salt flank and the borehole is required which does not include the salt, as shown in Figure 5a. The spatial uncertainly introduced by using only a generalized velocity field between the salt and borehole is considerably less significant than for the entire path from the surface to the salt which would have needed the complicated salt canopy.

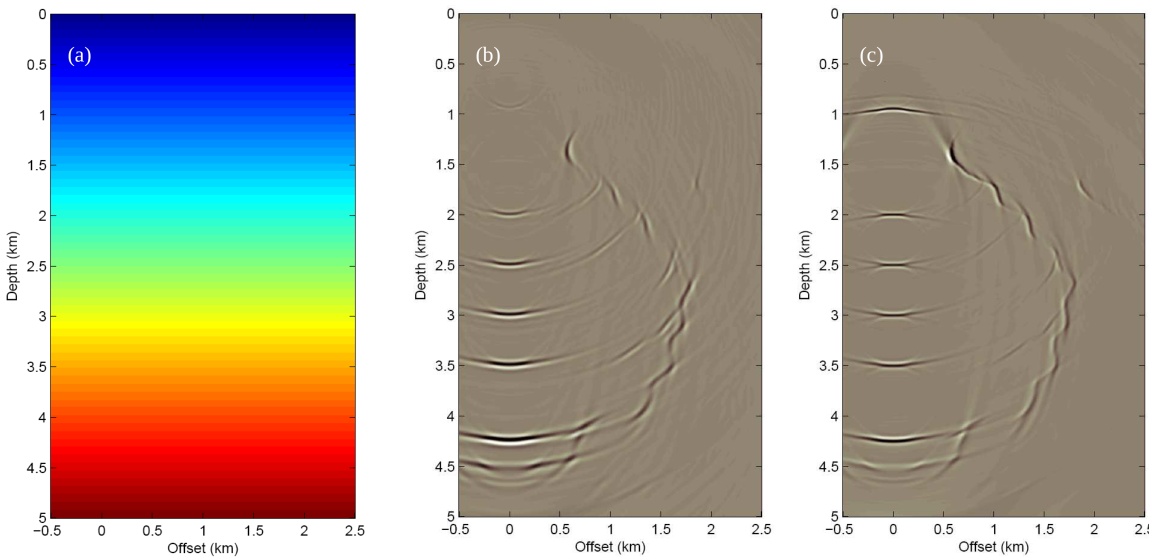

Figure 5: (a) Velocity model used in the first pass of migration which only has the simple $v(z)$ vertical velocity gradient; (b) migration results from reverse time pre-stack depth migration of the redatummed data; (c) migration results from reverse time prestack depth migration of the data created with downhole sources and receivers (benchmark case).

We applied the same reverse time prestack depth migration to both the redatummed common shot gathers and the actual modeled downhole common shot gathers (benchmark case). Figure 5b shows the migrated image using the redatummed data and Figure 5c shows the migrated image of the benchmark case. The image from the redatummed data is able to recover most of the salt edge in a similar fashion to the migrated benchmark results. Meanwhile both images illuminate very little of the dipping sediments.

Once the salt edge is delineated by the first pass of migration, we need to update our velocity model to include the salt for the second pass of migration. In practice we would do this by picking the interface between the salt and the background from the migrated image. However, we have not attempted to actually pick the salt edge from our first pass migrations. Instead by using the actual salt edge we show the best result that might be possible as shown in Figure 6a.

For the second pass, we apply the reverse time depth migration (which uses the two way wave equation) to both the redatummed data and benchmark data. These migration results are shown in Figure 6b and 6c, respectively. Because we include the salt dome in the velocity model and are using a full wave equation algorithm, we are able to catch the energy that bounces off the salt flank and illuminates the sediments. These second pass images show very good delineation of both the dipping sediments and the salt edge. Some new artifacts have crept into the image which might be reduced with further refinement of the migration algorithm and/or preprocessing of the data (e.g. Yoon et. al. 2004; Fletcher et. al. 2005; Guitton et. al. 2006a).

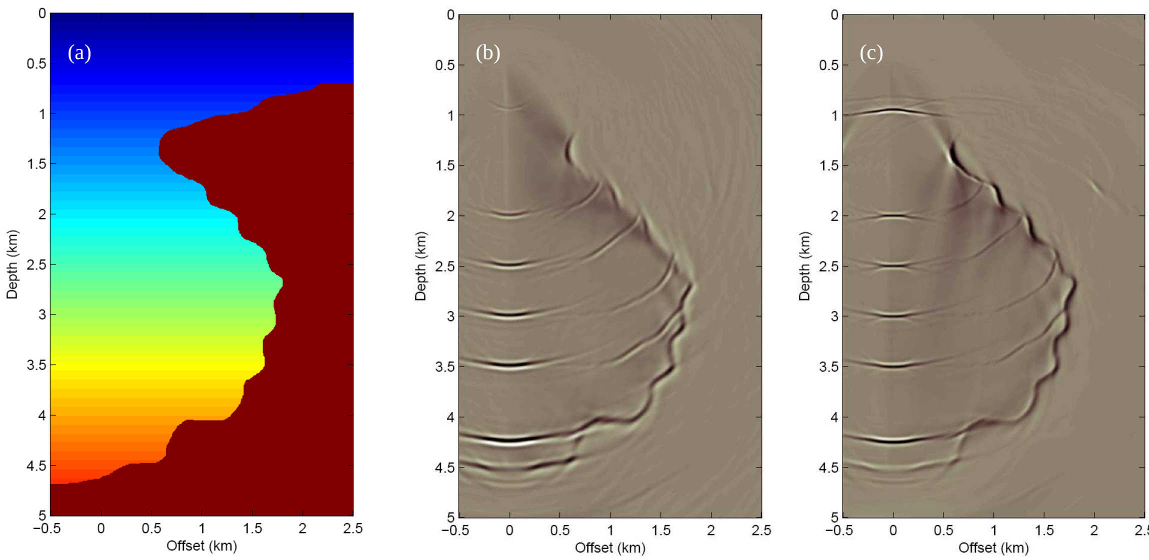

Figure 6: (a) Velocity model used in the second pass of migration which includes the salt dome that could be defined in the first pass; (b) migration results from reverse time pre-stack depth migration of the redatummed data; (c) migration results from reverse time prestack depth migration of the data created with downhole sources and receivers (benchmark case).

The two step processing strategy we propose in this section eliminates the need for many iterative steps of prestack depth migration in order to build the velocity model for the overburden. These steps have been replaced by the redatumming process which takes about ten percent of the total computational effort for the proposed strategy.

3. DISCUSSION

Comparing the results of the first pass of migration for both the benchmark and the redatummed cases (Figure 5b and 5c), both image the edges of the bottom half of salt dome with about the same quality. However, on the upper half of the salt dome, the undersides of the salt crenulations are much better defined in the benchmark image (Figure 5c). This is because the actual downhole source has a better chance to illuminate the underside of the salt and the receivers have captured the reflections. The redatummed shot records (Figure 4a) most likely suffers from a lack of aperture in the original WVSP. The sediment events have nearly the same amount of clarity on both the benchmark and redatummed images, with the benchmark case having slightly better quality.

The second pass of migration (Figure 6), which uses the salt dome velocity in the migration model, shows somewhat improved images of the salt interface. However the greatest improvement is seen in the sediments. Now the sediment interfaces are distinguishable for up to 0.75 km away from the salt edge until the dip of the sediments is nearly flat. At that point the acquisition geometry does not seem to capture reflections from horizontal events, except immediately around the borehole. Thus the redatumming step followed by two passes of reverse time migration has been able to capture the salt edge and dipping sediments. The reverse time migration has been able to utilize the multipath arrivals which have bounced off the salt edge to make this improvement.

Of course the issue that remains is whether a conventional prestack depth migration of the original WVSP data set would produce a comparable image – for example, what has been gained and what has been lost. To answer these questions, we perform a reverse time, prestack depth migration of the WVSP using the correct velocity model but with the salt dome removed, as shown in the left panel of Figure 7. The right panel of Figure 7 shows the migrated result. As with the redatummed result, the salt edge is imaged well, but the sediments near the salt are missing. However, to get to this point, additional iterations of depth migration and/or velocity model building would have had to be done in order to derive the top and bottom boundaries of the salt canopy.

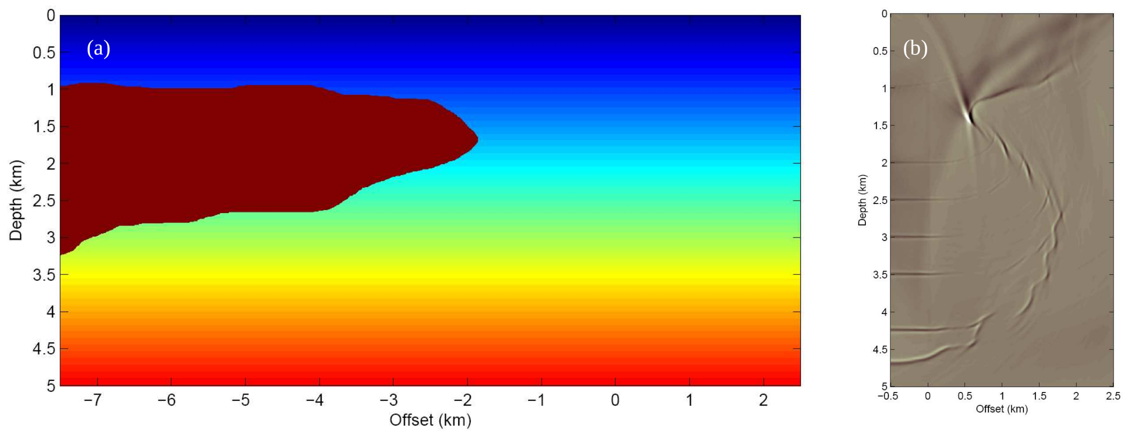

Figure 7: (a) Velocity model used in the first pass of WVSP migration which assumes that we already have a good knowledge of the salt canopy (SD-II); (b) migration results from reverse time pre-stack depth migration of the WVSP data.

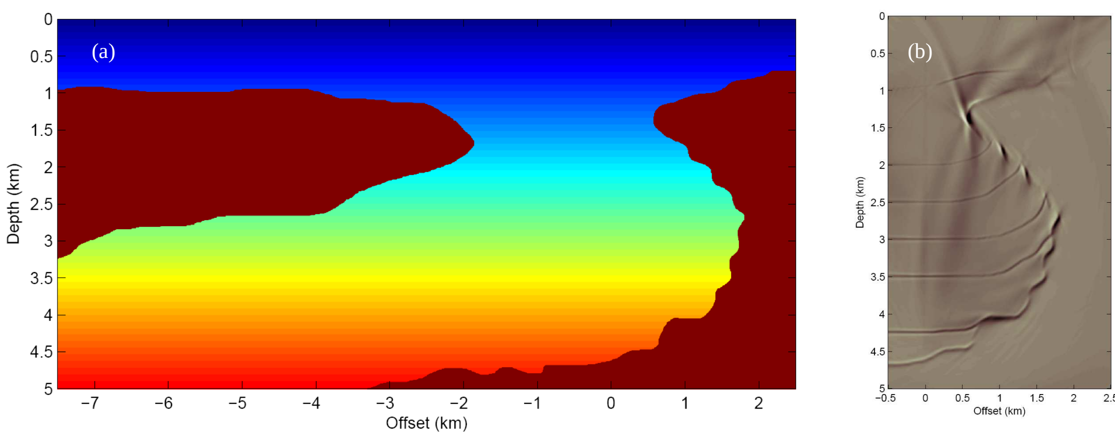

Figure 8: (a) Velocity model used in the second pass of WVSP migration which includes both the salt canopy (SD-II) and the salt dome (SD-I) that could be defined in the first pass; (b) migration results from reverse time pre-stack depth migration of the WVSP data.

We next apply a second pass of depth migration to the WVSP using the completely correct velocity model containing the salt dome (Figure 8a). The final migrated result is shown on the right side of Figure 8. The migrated WVSP image from Figure 8b and the migrated image of the redatummed VSP from Figure 6b are plotted side by side in Figure 9 for easy reference. Overall we see that both methods have imaged most of the salt edge very well. However, the undersides of the crenulations on the top half of the salt dome are not very clear on either section. The WVSP image has reproduced the sediments reflections all the way across the section and up to the salt edges. The redatummed result captures the horizontal portion of the sediments only extremely close to the borehole but obtains a reasonable image of the dipping portion near the salt.

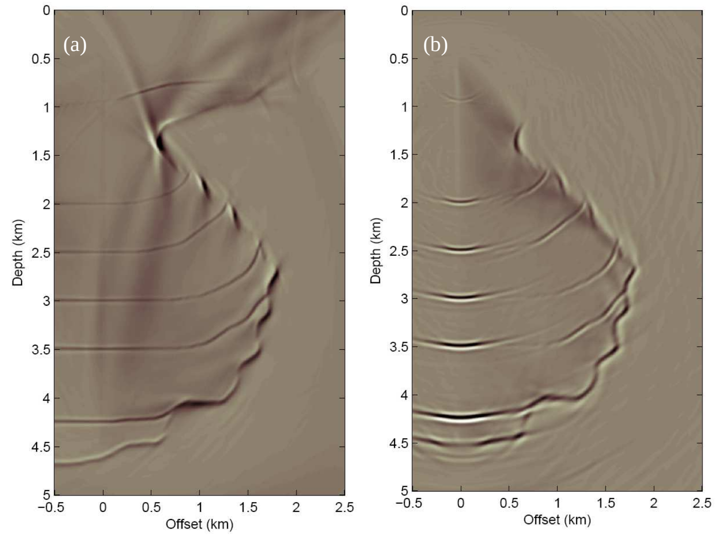

Figure 9: Comparison of second pass migration results of (a) the WVSP data, and (b) the redatummed data.

For reference, we include a Kirchhoff, prestack depth migration of modeled surface seismic data. We used an Eikonal solver (Podvin and Lecomte, 1991; Lomax, 2000) to create the travel time tables for the migration using the exact velocity model (Figure 1). The migrated image is shown in Figure 10. As with the other first pass migrated results, the up dipping sediments are missing from this image.

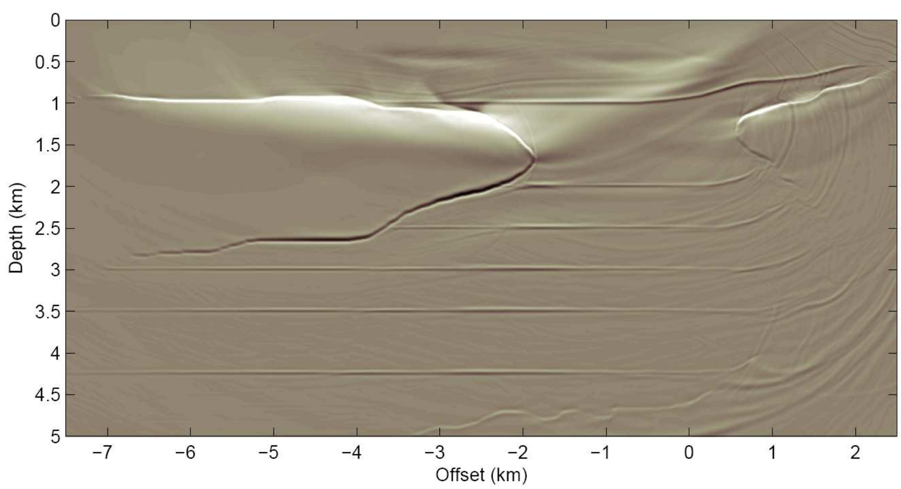

Figure 10: Result from Kirchhoff prestack depth migration of a modeled surface seismic data using the exact forward velocity model shown in Figure 1.

In this paper we have described a strategy to perform a short cut approach to image the sediments and salt edge around a salt flank through a complex overburden using a WVSP data set. Traditionally, depth migration utilizes numerous iterations of migration, velocity estimation and model building. The short cut of redatumming the WVSP data to be as if an effective downhole survey had been collected with shots and receivers in the borehole allows us to ignore all of the velocity issues associated with the overburden. We have not discussed the issues of velocity estimation for the simple $v(z)$ background velocities used in our migrations. We believe that having relocated our frame of reference to be from the borehole perspective, that the image uncertainty associated with velocity errors have been greatly reduced since the distance from the well bore to the salt flank is typically comparatively small. Also, we have not attempted to actually pick the salt edge from our first pass migrations to build the model for the second pass migration. Instead we show the best that might be possible by using the actual salt edge. Obviously, the success of this method on actual field data will depend on data quality, field acquisition parameters including aperture and source and receiver spacing, as well as the actual geometry of the salt bodies.

4. CONCLUSION

We have presented a strategy for imaging the flanks of a salt dome when there is an obscuring salt canopy present in the immediate area. The first step performs a redatumming of a walk away VSP data set so that we obtain effective downhole shot gathers. Then we apply two passes of reverse time prestack depth migration. The use of the two way wave equation allows us to image both the salt dome edge and the dipping sediments. The method is target oriented and is at least three times faster than a comparable imaging effort on the original walk away VSP data. It also eliminates the need for iterative depth migrations of the complex overburden. The final image we obtain of the salt edge and the dipping sediments, while not as complete as the walk away VSP results, provides a short cut method to a useful image.

Of course, as with all migration methods, the strategy requires an adequate acquisition aperture to capture the salt dome and sediment reflections. The formalism we present was tested on acoustic model data. Additional work needs to be done to extend this to elastic, multicomponent data sets. The performance of this strategy on field data will need to be done to test its sensitivity to noise sources.

5. ACKNOWLEDGEMENTS

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